Renewable and Sustainable Energy Reviews 15 (2011) 815–820

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment of wind energy potential and optimal electricity generation in Borj-Cedria, Tunisia

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ARTICLE INFO

Article history:
Received 12 May 2010
Accepted 14 July 2010

Keywords:
Wind energy potential
Wind turbine
Power losses
Net energy output

ABSTRACT

In the last century, several climate changes have been observed in regions all over the world. The main cause of these climatic changes is the rise of fossil fuel uses, which is due to the important demographic and industrial development. These negative effects have forced scientists to draw attention to renewable energy sources, which are the most suitable solution in the future. In this paper, wind energy potential was estimated using the wind speed data collected by two meteorological stations installed in the Centre of Research and Technologies of Energy (CRTEn) in the Borj-Cedria area. The data collected at 30, 20 and 10 m height during 2008 and 2009, have permitted us to estimate the seasonal mean wind speed, wind speed distribution and wind power density. The results have been used to estimate the net energy output of seven 1.5 MW wind turbines with taken account the air density correction and the power losses in wind farm. This comparative simulation shows difference in wind generators production and allows us to choose the best wind turbine adapted to the site conditions.

Contents

1. Introduction

The carbon dioxide CO_2 is the most important gas with greenhouse effect. Its annual emissions have increased by approximately 80% between 1970 and 2004 according to the Intergovernmental Panel on Climate Change IPCC [1]. In 2005, atmospheric CO_2 concentrations reach 379 ppm and largely exceed the natural range over the last 650 000 years. The main cause of this rise is essentially the use of fossil fuels. In addition, the linear warming of the globe surface over the 50 years from 1956 to 2005 (0.13 °C per decade) is nearly twice that for the 100 years from 1906 to 2005.

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1364-0321/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2010.07.020

To cure this problem, renewable energy such as solar, wind and hydraulic energy, should be a sustainable solution in the future. Recently, an interest in wind energy has been growing and many researchers have attempted to develop and to perform reliable wind energy conversion systems. One of the most important problems in this general context is the implantation of wind park. In fact, due to the great investment in this kind of project, many researchers have studied the wind energy resources in sites all over the world. Many others have tried to optimize the capacity generation of the wind farm by choosing the suitable model of wind turbine.

In the United State of America, the world leader in the field of wind energy capacity since 2008 [2], Raichle and Carson [3] have studied the wind resource of the Southern Appalachian Mountain region in the Southeastern United States. They have used data collected at 50 m above ground level on nine ridge top sites in the period between 2002 and 2005. Wichser and Klink [4] have used the data collected in four sites in Minnesota during three years at the altitude of 70–75m to estimate the wind resources in this location. They have also conducted a comparative simulation of three configurations of the GE 1.5 MW series wind turbine to evaluate the potential gain in power production that may be realized with low wind speed technology. Kose et al. [5] have evaluated the wind energy potential in Kutahya by means of data collected for 20 months at 10 and 30 m mast high. Kose [6] has also discussed the production of the Enercon 600 kW wind turbine in the same site. The wind energy potential of Gokceada Island has been evaluated in the study conducted by Eskin et al. [7] using the wind data collected in four different locations in Island at two altitudes. Gökçek and Genç [8] have evaluated the electricity generation and energy cost of eight wind energy conversion systems in many locations at Central Turkey. Ouammi et al. [9] have studied the wind energy potential in Liguria region in Italy from the data collected by 25 stations distributed over the four provinces. Himri et al. [10] have presented an analysis of data collected between 2002 and 2006 in four selected sites in Algeria as well as preliminary evaluation of the wind energy potential. A comparative simulation of wind park design and siting in five locations in Algeria has been presented by Ettoumi et al. [11]. They have compared nine commercialized wind turbine with different power output. In the Saudi Arabia, Rehman et al. [12] have presented an analysis of wind speed data and available energy in Rafha area using wind machines of 600, 1000 and 1500 kW sizes from three manufacturers. Al-Abbadi [13] has also presented the wind energy resource assessment for five locations in Saudi Arabia using the collected data over a period spanned between 1995 and 2002. Ahmed Shata and Hanitsch [14,15] have studied in two different papers the wind energy potential and the electricity generation in Hurghada and in the coast of Mediterranean sea in Egypt.

All researchers have concluded that to maximize the energy output of wind project, we should design a wind turbine model that agrees with the wind resources of the region. So, a wind turbine can reach its maximum efficiency if it is designed especially for the region of implantation. However, it is expensive to design a wind turbine for one region. Therefore, a simulation must be conducted to choose the suitable one among existing machines.

In Tunisia, the government has taken steps to reduce its dependence on imported oil products, which negatively affects its trade balance, by adopting a strategy aimed at increasing the use of renewable energy. So, in 2000 the first wind farm in Tunisia was implemented in Sidi Daoud site with an initial capacity of 10.56 MW. Rapidly this capacity has been evolved to reach 53.6 MW [16]. Recently, three new wind park projects will be implanted in the site of Metline and Kechabta in Bizerte province with a total capacity of 120 MW [17]. Therefore, the avoided CO_2 emissions would be approximately 330 000 tons. However, little studies have been presented in this sector in Tunisia. We note essentially the study conducted by Ben Amar et al. [18]. They have presented the energy assessment of the first wind farm section of Sidi Daoud using the data collected between 2000 and 2004. Elamouri and Ben Amar [19] have also evaluated the wind speed characteristics and the wind power potential for 17 locations in Tunisia. They have used the hourly meteorological data provided by the Meteorology National Institute at an altitude of 10 m above ground level.

In this study an assessment of wind energy potential and optimal electricity generation in the site of Borj-Cedria was presented. The wind speed distribution, wind power density and mean wind speed are estimated. The data collected at 10, 20, and 30 m height during 2008 and 2009 and the technical data provided by seven wind turbine manufactures have permitted us to calculate the seasonal net energy production in this area. The aim of this paper is to evaluate the feasibility of wind park project in Borj-Cedria and to present the best 1.5 MW wind turbine adapted to the site condition.

2. Site description

Tunisia is situated on the Mediterranean coast of North Africa with a surface of 163 610 km^2. It is bordered by Algeria in the west and Libya in the south-east. The country is divided in two regions, the well-watered north and the semi-arid south. The climate is directly influenced by the marine wind with over than 1298 km of coasts.

The majority of the electricity used in Tunisia is produced locally by stateowned company STEG. According to Fig. 1 the electricity production in Tunisia is based in thermal steam and combined cycle [20]. Electricity from renewable resources does not exceed 2%. This value will attain 4% with the starting of three new wind farms in the area of Bizerte [17]. STEG has encouraged, since April 2009, the privatization of wind electricity production and has fixed at 0.068 USD/kW h the price of purchase of the electricity generated by high and average voltage wind systems.

In this study, two NRG metrological stations were installed in the Center of Research and Technology of Energy (CRTEn) in Borj-Cedria area, at 25 km at the southern suburbs of Tunis City. These stations are equipped with an acquisition system which records, every 10 min the average, the maximum, the minimum and the standard deviation values for each sensor. The data are saved in a flash memory card and treated via the NRG symphony data retriever program.

3. Theoretical model

The most important parameter that should be estimated while designing a wind park is the wind power density of the site. Even this parameter is estimated, there is mainly two ways to calculate the energy produced by a given wind turbine. The first is to directly use the data collected in the site and the power curve of the studied wind turbine. The second one consists in the use of the probability

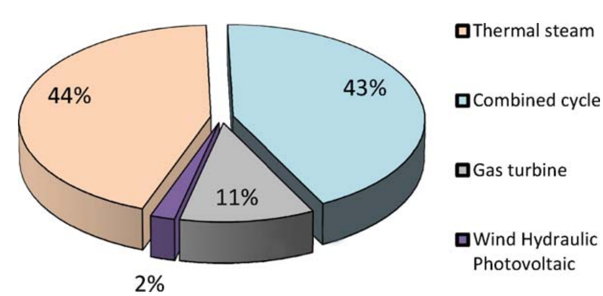

Fig. 1. Sources of electricity production in Tunisia.

distribution function and the performance coefficient curve of the studied wind turbine. In each of these two methods, an empirical model must be used to estimate even the wind speed or the Weibull parameters at the wind turbine hub high.

3.1. Weibull distribution

Weibull distribution has been commonly used in literature to express the wind speed frequency distribution and to estimate the wind power density. The main advantage of this function is the simplicity of the annual production calculation for any wind turbine. The probability density function of Weibull distribution is given by

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left(-\left(\frac{V}{c}\right)^{k}\right) \quad (1)$$

where *f*(*V*) is the probability density function, *c* and *k* are respectively the scale and the shape parameters which can be calculated using Eqs. (2) and (3) [21].

$$k = \left(\left(\frac{\sum_{i=1}^{n} V_i^k \ln(V_i)}{\sum_i V_i^k}\right) - \left(\frac{\sum_{i=1}^{n} \ln(V_i)}{n}\right)\right)^{-1} \quad (2)$$

$$c = \left(\frac{\sum_{i=1}^{n} V_i^k}{n}\right)^{1/k} \quad (3)$$

where n is the observation number and V_i the wind speed.

3.2. Wind power density

The wind power density is generally considered as the best indicator of the wind resource in the site. In fact, this parameter takes into account the wind speed, the wind speed distribution and the air density. For a series of measurement, the mean wind power density is calculated as

$$\bar{p} = \frac{1}{2}\rho\overline{V^3} \quad (4)$$

Eq. (4) depends on the frequency of each velocity, therefore mean wind power density can be expressed as

$$\overline{p} = \int_0^{\infty} \frac{1}{2}\rho V^3 f(V) dV \quad (5)$$

Once knowing the technical characteristics of a given wind turbine and the Weibull distribution in the site, Eq. (5) is used to determine the average of annual production.

3.3. Wind speed extrapolation

The wind speed measurements are collected in the site at 10, 20 and 30 m above ground level. For wind projects, it is necessary to estimate the wind speed at the turbine hub height. According to the literature, the most commonly used method to adjust the wind velocity at one level to another is the power law method [22] expressed by

$$V = V_{mes}\left(\frac{h}{h_{mes}}\right)^{\beta} \quad (6)$$

where V_{mes} is the wind speed recorded at anemometer height h_{mes}, V is the wind speed to be determined for the desired height h and β is the power law exponent estimated using the wind speed measurement at the three altitudes.

3.4. Air density estimation

The air density is defined as the mass of a quantity of air divided by its volume. This parameter has a great importance in the estimation of the power density and it depends essentially on the ambient temperature and the barometric pressure. So, to calculate the air density we commonly use the following expression [23]

$$\rho = 3.484\frac{P}{T} \quad (7)$$

where P is the air pressure and T is the air temperature.

3.5. Power loss factor

According to the climatic observation conducted in the studied site, different losses can influence the performance of the wind turbine.

We find essentially:

- The downtime losses which represent the energy lost when the turbine is offline due to scheduled maintenance or repair.
- The aerodynamic losses resulting from the interference between wind turbines in a wind farm.
- The electrical losses like transformer and wiring losses.
- Losses due to cut-out at high wind speeds.

For the modern wind turbine, losses are expressed in percent of energy produced and it does not exceed 20% in the major of cases. In this study, the value of the power losses factor is evaluated using Eq. (8) and it is equal to 14.27%.

$$F = 1 - (1 - f_{downtime})(1 - f_{aero})(1 - f_{icing})(1 - f_{other}) \quad (8)$$

where $f_{downtime}$ is the downtime losses factor, f_{aero} is the aerodynamic losses factor, f_{icing} is the icing/soiling losses factor and f_{other} is the other losses factor.

3.6. Power output

The major wind turbine manufactures give actually the power curve of their product in the technical note. So, it is simple to estimate the power output of any wind turbine when a series of measurement is conducted in the studied site. However, in several cases only the probability distribution function is available. In this situation the power output for each wind speed can be expressed as

$$P = C_p(V)S\frac{1}{2}\rho V^3 \quad (9)$$

where $C_p(V)$ is the performance coefficient of the wind turbine at the wind speed V and S is the wind turbine rotor area.

In this study, over 105 420 observations have been collected in the site. For that reason, we use directly the curves given by the manufactures to estimate the power output at each time step. According to the recommendations of the International Electrotechnical Commission (IEC standard 61400-12-1 (2005)), an air density correction must be performed to account for any difference between the actual air density and the air density at which the power curve applies. This correction depends on the aerodynamic regulation system used in the wind turbine. For a stall-controlled wind turbine, we first calculate the power output predicted by the given power curve for the measured wind speed, and then we adjust the power output according to the following equation

$$P = P_0\frac{\rho}{\rho_0} \quad (10)$$

where P_0 is the power output predicted using the power curve and the wind speed in the current time step, ρ is the actual air density in the current time step calculated with Eq. (7) and ρ_0 is the air density at which the power curve applies.

For a pitch-controlled wind turbine, we first calculate the effective wind speed resulting from the current air density and then we refer to the given power curve to find the power output predicted at that effective wind speed.

The following equation gives the effective wind speed

$$V_{eff} = V_0 \left(\frac{\rho}{\rho_0}\right)^{1/3} \quad (11)$$

where V_0 is the actual wind speed recorded in the current time step.

3.7. Mean net power output

Once we have calculated the power output of the wind turbine in each time step, we estimate the mean net power output using Eq. (12).

$$\bar{P} = (1 - F)\frac{1}{n}\sum_{i=1}^{n} P_i \quad (12)$$

where P_i is the wind turbine power output before losses.

The mean net energy output for a period of time will be calculated as

$$E = \bar{P} \cdot \Delta t \quad (13)$$

where Δt is the time period.

For the annual wind energy estimation the value of 8640 h is used.

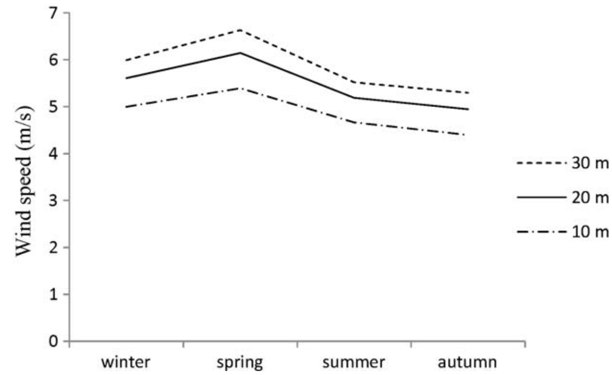

Fig. 2. Seasonal mean wind speed.

4. Results and discussion

4.1. Wind speed

Fig. 2 shows that the highest values of seasonal mean wind speed are observed during spring. However, the lowest values are recorded in autumn. The annual mean wind speeds are respectively equal to 5.853, 5.467 and 4.895 m/s at 30, 20 and 10 m. These values exceed the cut-in wind speed for the major commercialized wind turbines and show that the site of Borj-Cedria presents a good wind resource. It is important to note, also, that the highest value of wind speed is recorded in the autumn and it is equal to 23.310 m/s, which not exceed the cut-out wind speed recommended for all wind turbines.

4.2. Wind speed distribution and wind power density

In order to evaluate the probability density function, Weibull distribution for each season is obtained. The seasonal probability

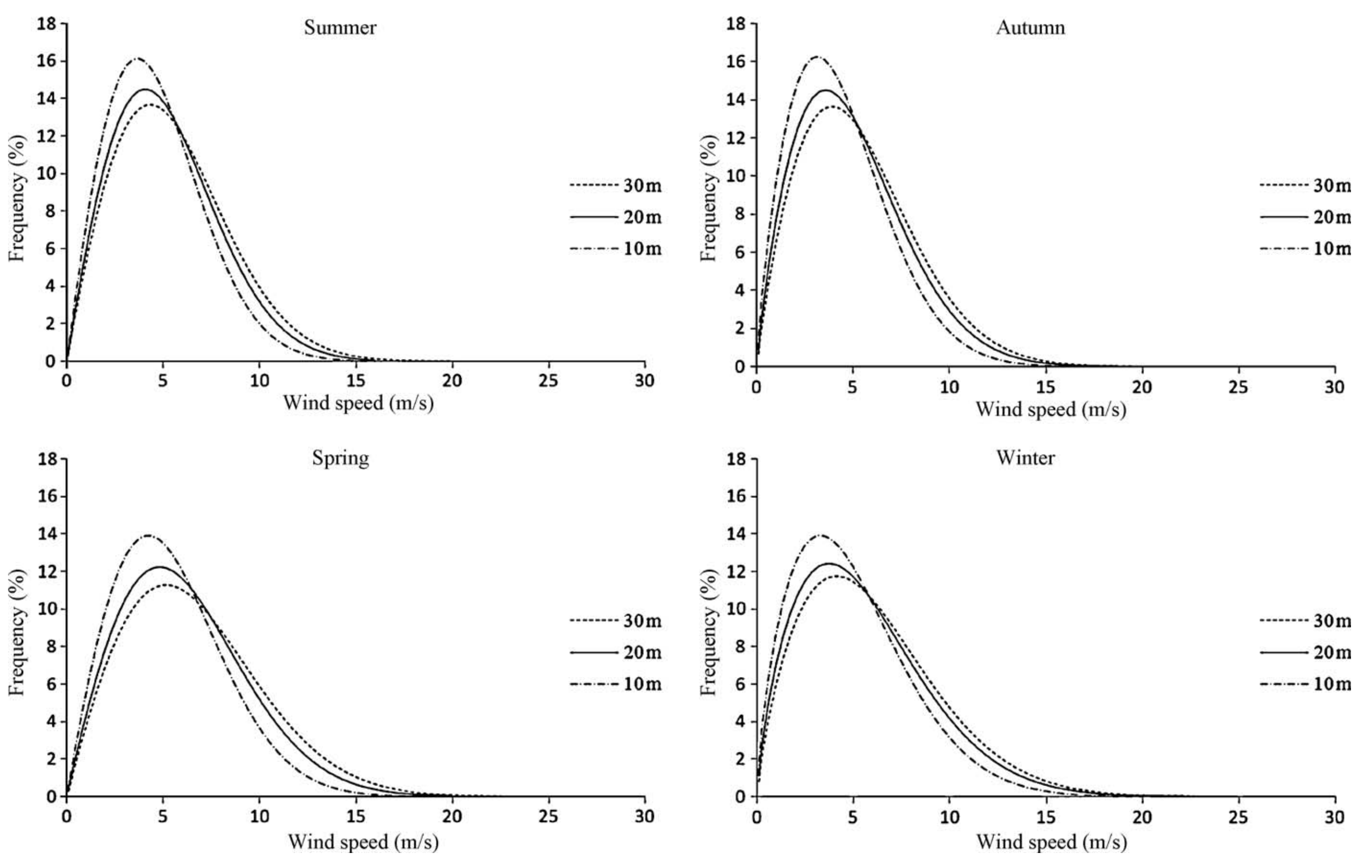

Fig. 3. Seasonal wind speed frequency distributions in the site.

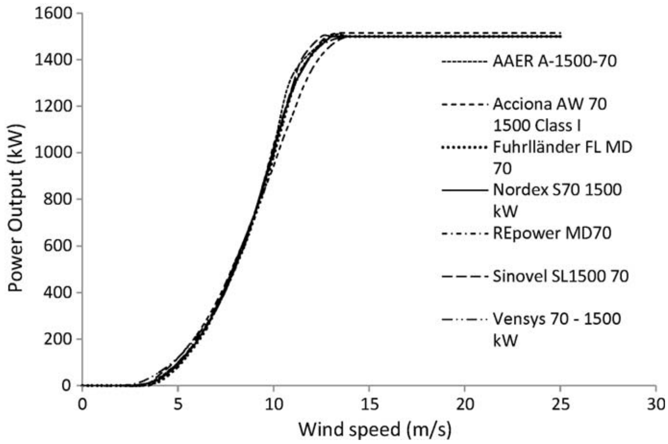

Fig. 4. Power curves of studied wind turbines.

Table 3
Technical characteristics of studied wind turbines.

Description	Manufacture	Rated output (kW)	Diameter (m)	Aerodynamic regulation
AAER A-1000	AAER	1500	70	Pitch control
Acciona AW 70/1500 Cl I	Acciona	1500	70	Pitch control
Fuhrländer FL MD 70	Fuhrländer	1500	70	Pitch control
Nordex S70/1500 kW	Nordex	1500	70	Pitch control
REpower MD70	REpower Systems	1500	70	Pitch control
Sinovel SL1500/70	Sinovel	1500	70	Pitch control
Vensys 70 – 1500 kW	Vensys Energie systeme	1500	70	Pitch control

density distributions derived from the data collected in the site at each altitude are shown in Fig. 3. The peak of probability values are observed in summer and autumn while the lowest values are observed in spring (Fig. 3).

The seasonal Weibull parameters *c* and *k* are presented in Table 1. As seen, Weibull scale parameter *c* varies between 7.460 and 4.943 m/s while shape parameter *k* varies between 1.964 and 1.688. The highest value of *c* is obtained in spring where the wind is usually regular with a high speeds. Furthermore, highest value of *k* parameter is observed in the summer where the sea breeze phenomenon influences considerably the wind speed in this season.

Table 2 shows a large variation of wind power density from season to season. We note that the highest values of seasonal wind power density are observed in spring in contrast the lowest values are calculated in summer and autumn. The obtained results give good information about the site and confirm, again, that Borj-Cedria presents an important wind potential.

4.3. Wind turbines net energy production

In this part of paper, we are interested to the optimization of the capacity generation of a wind park project in the studied site. In fact, the industry of wind turbine has considerably evolved principally in Germany, Netherlands, USA, Canada, Spain and France. A large variety of manufactured wind generators provide electric power between 0.25 and 5000 kW. In our study, we have evaluated and compared the seasonal net energy production of seven commercialized 1.5 MW wind turbines supposed to be installed at 80 m above ground level. The technical data of these seven wind machines are summarized in Table 3.

Fig. 4 presents the curves of the studied wind turbines given by each manufacture for an air density equal to 1.225 kg/m^3. As shown, the power output of wind turbines quickly increases and takes its maximum value at the nominal wind speed of approximately 12 m/s. The cut-in wind speed of the studied turbines is about 3.5 m/s. However, the cut-out wind speed does not exceed 25 m/s.

To estimate the energy output of each wind turbine, a procedure was developed. So, in every time step, the air density, the power exponent and the power output of wind turbines are estimated. The air density correction and the power losses factor permit us to calculate with accuracy their net energy output.

Figs. 5–8 represent the seasonal net energy output for the seven wind turbines in each season. We note a difference between the wind turbines production. In fact, the Vensys wind turbine has the highest energy production in winter, summer and autumn. However, the wind turbine AAER presents the highest production in spring with a value of 1 123 666 kW h/year, which represents the maximum seasonal net energy output for all studied wind turbines. The Fuhrländer wind turbine seems to have the least performance in the site with the minimum energy production equal to 613 422 kW h/year.

Table 1
Seasonal Wiebull parameters at various altitudes.

Altitude (m)	Parameter (m/s)	Winter	Spring	Summer	Autumn
30	*k*	1.736	1.936	1.964	1.841
	c	6.723	7.460	6.208	5.960
20	*k*	1.695	1.962	1.963	1.807
	c	6.286	6.921	5.837	5.565
10	*k*	1.688	1.961	1.963	1.799
	c	5.600	6.074	5.246	4.943

Table 2
Seasonal wind power density.

	Altitude (m)	Winter	Spring	Summer	Autumn
p (w/m^2)	30	289	372	186	188
	20	248	271	155	158
	10	176	183	113	111

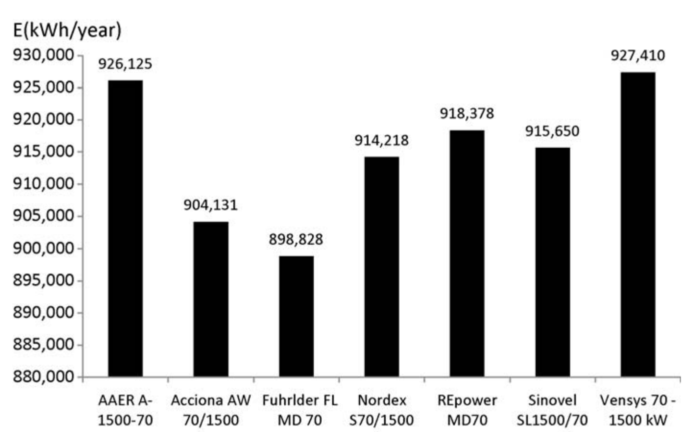

Fig. 5. Winter net energy output.

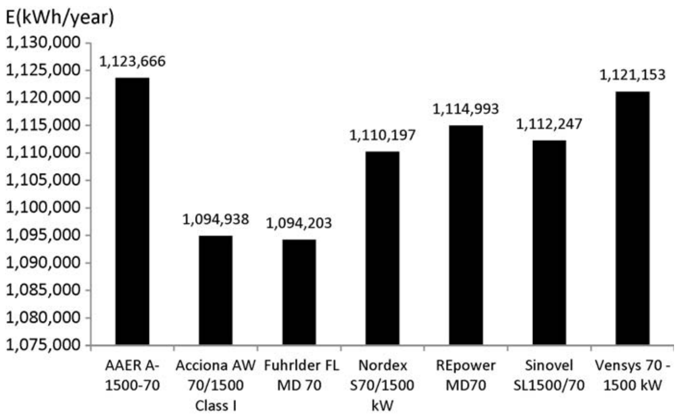

Fig. 6. Spring net energy output.

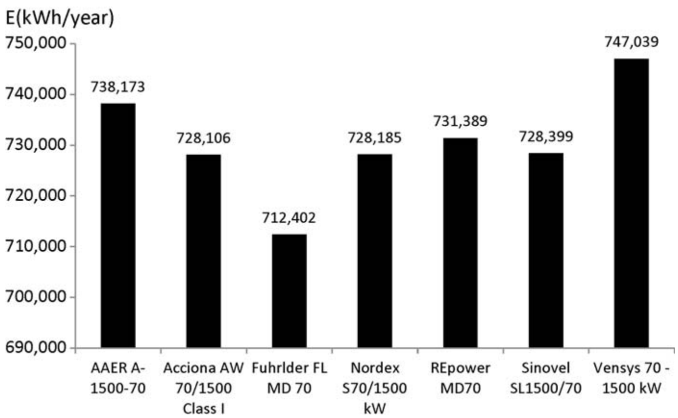

Fig. 7. Summer net energy output.

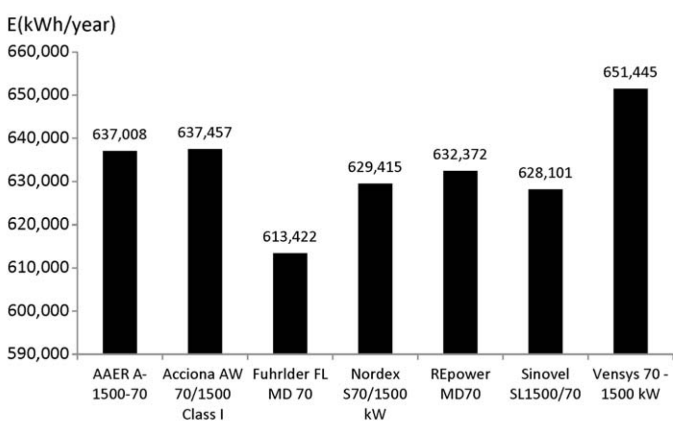

Fig. 8. Autumn net energy output.

As a result, we can classify the studied wind turbines in three categories. The first group includes the wind turbine Vensys and AAER, which have the best annual production. The second category comprises the wind turbine Nordex, REpower and Sinovel, with a near seasonal production. The wind turbine Acciona and Fuhrländer represent the third category with the least energy output.

5. Conclusion

In this paper, the electrical capacity generation of the site of Borj-Cedria in Tunisia is discussed. The mean wind speed, the wind probability distribution function and the wind power density are presented for each season at three altitudes. The results prove that the site of Borj-Cedria presents a promising wind potential. The simulation of the production of seven commercialized wind turbines shows about 3.57% of differences in the annual net energy production and confirms that the Vensys70 wind turbine is the best type adapted to the site condition. The present study confirms the feasibility of a wind park project in Borj-Cedria and the importance of choosing the suitable type of wind turbine for the site.

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